

A coupled model of magnetic flux generation and transport in stars*

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We present a combined model for magnetic field generation and transport in cool stars with outer convection zones. The mean toroidal magnetic field, which is generated by a cyclic thin-layer $\alpha\Omega$ dynamo at the bottom of the convection zone is taken to determine the emergence probability of magnetic flux tubes in the photosphere. Following the nonlinear rise of the unstable thin flux tubes, emergence latitudes and tilt angles of bipolar magnetic regions are determined. These quantities are put into a surface flux transport model, which simulates the surface evolution of magnetic flux under the effects of large-scale flows and turbulent diffusion. First results are discussed for the case of the Sun and for more rapidly rotating solar-type stars.

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1 Introduction

The increasing observational knowledge on stellar magnetic activity makes it possible to use the observed activity patterns to constrain stellar dynamo models (Strassmeier 2005; Collier Cameron 2007; Holzwarth, Mackay & Jardine 2007). On the one hand, many solar and stellar dynamo models in the literature make the assumption that the toroidal magnetic fields created in stellar interiors represent also the surface emergence patterns. On the other hand, numerical simulations of the rise of flux tubes in the convection zone (Caligari, Moreno-Insertis, & Schüssler 1995) have been successful in reproducing the observed properties of sunspot groups, among which e.g., the tilt angle is of particular importance in surface flux transport models and Babcock-Leighton-type dynamos (Dikpati & Charbonneau 1999). Therefore, it is now possible to consider in a consistent way the interrelations between the dynamo mechanism operating in stellar interiors, transport of toroidal magnetic flux in the convection zone, and the emerging flux which evolves under the effects of surface flows. Our approach combines models for three processes: 1) the dynamo operating in the overshoot layer at the bottom of the convection zone, 2) stability and rise of magnetic flux tubes through the convection zone, 3) transport of magnetic flux on the surface.

2 The model

We consider stars with solar internal structure and differential rotation, keeping the difference between the minimum

and maximum angular velocities, $\Delta\Omega$, independent of the stellar rotation rate, which is a plausible assumption for rapidly rotating stars (e.g., Barnes et al. 2005). The only stellar parameter that we vary is the surface rotation period at the equator, P_{rot} .

The dynamo model. The generation of magnetic flux is described by a dynamo model, which provides the toroidal component of the mean magnetic field. As a simple example, here we consider an $\alpha\Omega$ dynamo operating in a thin layer at the bottom of the convection zone (Schmitt & Schüssler 1989). We assume a Sun-like radial differential rotation profile, according to helioseismic observations (Schou et al. 1998). A negative α -effect is assumed for latitudes below 35° , where the radial shear is positive. This choice is motivated by an α -effect due to flux tube instabilities (Ferriz Mas, Schmitt & Schüssler 1994) or unstable magnetostrophic waves (Schmitt 2003). The maximum strength of the α -effect (at $\lambda = \pm 17.5^\circ$) is assumed to be proportional to the stellar equatorial rotation rate, Ω_0 . The turbulent diffusivity of $5.6 \cdot 10^{11} \text{ cm}^2 \text{ s}^{-1}$ is chosen such that the cycle period becomes 11 years in the case of the Sun.

The rise of flux tubes in the convection zone. In this part of the model, the thin flux tube approximation is considered. Magnetic flux tubes are assumed to form (e.g., by magnetic Rayleigh-Taylor instability) within a layer of toroidal magnetic field created by the radial shear in the upper tachocline. When the field strength of a tube exceeds a threshold, the Parker (undulatory) instability sets in, and the flux tube forms one or two rising loops. The probability for a flux tube to erupt from a given latitude λ and at a given time t is assumed to be proportional to the mean toroidal field, $B(\lambda, t)$, provided by the dynamo model. The total number of erupting flux tubes per activity cycle is scaled with Ω_0 , in accordance with the observed relation between rotation and activity (e.g., Montesinos et al. 2001). Considering the lin-

* Movies are available via <http://www.aip.de/AN/movies>

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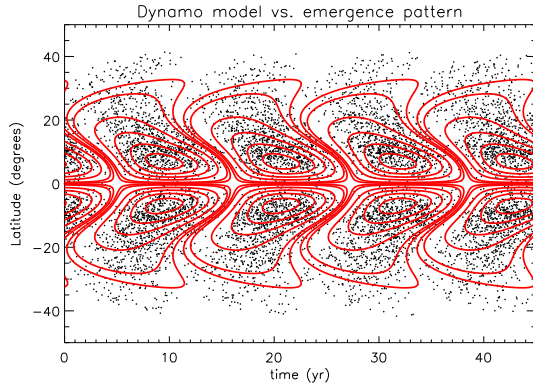


Fig. 1 Time-latitude diagram of the dynamo-generated mean toroidal magnetic field $B(\lambda, t)$ at the bottom of the convection zone (contours) and of the flux loops emerging at the surface (dots) for a Sun-like star with $P_{\text{rot}} = 27$ d. The dynamo waves and the emergence pattern closely match in this case.

ear stability of flux tubes in the mid-overshoot region (Ferriz Mas & Schüssler 1995), unstable flux tubes near the stability limit are chosen. The corresponding field strengths are around 10^5 G for the case of the Sun. Having determined the eruption times, initial latitudes, and the corresponding field strengths of the individual flux tubes, we perform simulations of their buoyant rise (cf. Caligari et al. 1995) in order to determine the emergence latitudes and the tilt angles of the resulting bipolar magnetic regions at the surface. The separation of large bipolar regions on the Sun corresponds to much higher azimuthal wavenumbers ($m = 10 - 60$) than found for Parker-unstable flux tubes ($m = 1 - 2$). A solution to this problem is not available yet. There are, however, indications that bipolar regions dynamically disconnect from their roots at depths of only a few Mm below the surface and at an early stage of emergence, and this limits the azimuthal separation of emerging bipoles (Schüssler & Rempel 2005).

Surface flux transport. The emergence times, latitudes, and tilt angles resulting from the previous step are taken as the input (source term) for a surface flux transport model (Baumann et al. 2004, 2006). The source term defines bipolar magnetic regions as a function of position and time. The flux transport code simulates the evolution of purely vertical magnetic fields at the surface, under the effects of Sun-like latitudinal differential rotation, meridional flow, and supergranular diffusion. The emergence longitudes of bipolar regions are assumed to be randomly distributed. The areas of the bipolar regions are determined at random with a number distribution $N(A) \sim A^{-2}$, which represents the observed distribution of solar bipolar magnetic regions (Schrijver & Harvey 1994).

3 Results

First we consider the Sun-like case with $P_{\text{rot}} = 27$ d. Figure 1 shows the time-latitude diagram of the dynamo-

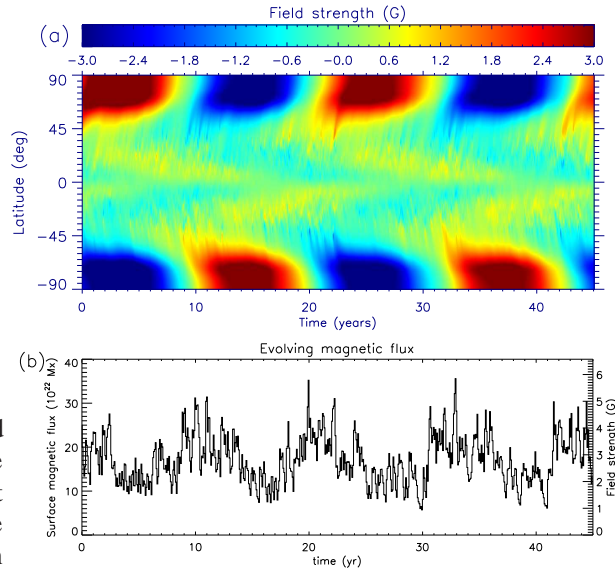


Fig. 2 (a) Time-latitude diagram of the azimuthally averaged strength of the radial surface magnetic field for the solar model. (b) Time variation of the surface-integrated magnetic flux. The values are averaged over 27-day time intervals.

generated toroidal magnetic field at the bottom of the convection zone and the locations of flux emergence. The toroidal field contours almost coincide with the overall emergence pattern, because of the small poleward deflection of rising flux tubes for a slow rotator like the Sun. This result justifies an implicit assumption that is often made when interpreting solar dynamo models: the surface activity pattern reflects the dynamo wave pattern. Azimuthal averages of the radial surface magnetic field are shown in a time-latitude diagram in Fig. 2a and the time evolution of the total surface magnetic flux is given in Fig. 2b. The values are close to the results of Baumann et al. (2004), with the exception that polar fields are slightly weaker in our case. The reason is that the tilt angles resulting from the flux tube rise are systematically smaller than for the functional latitude dependence assumed by Baumann et al. (2004), but actually provide a better match to the observations (see Fig. 12 in Caligari et al. 1995). An animation of the evolving surface flux is given in the supplementary file `Bsurf_27d.gif`.

We next consider a star with a rotation period of 10 d. The generated toroidal field and the emergence patterns are shown in Fig. 3. In this case, the poleward deflection of rising flux tubes is stronger than in the case of the Sun. The responsible effect is the component of the Coriolis force, directed towards the rotation axis (resulting from a flow along the flux tube in order to conserve angular momentum), and is proportional to the rotation rate. As shown in Fig. 4a, we have strong polar fields (note the different saturation level of the colour table, as compared to Fig. 2a). This is due to 1) higher emergence rate, 2) larger tilt angles owing to faster rotation. An animation of the evolving surface flux is given

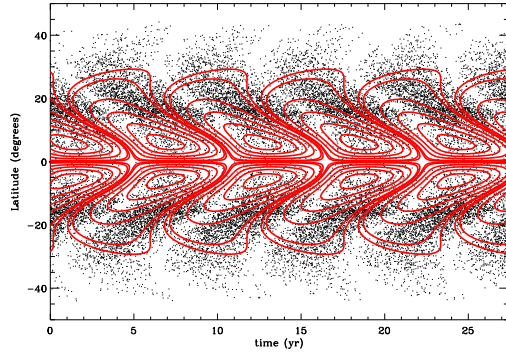


Fig. 3 Same as Fig. 1, for $P_{\text{rot}} = 10$ d.

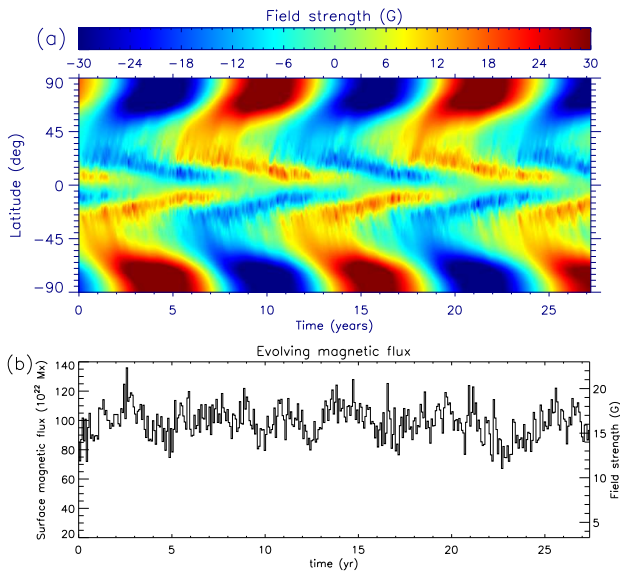


Fig. 4 Same as Fig. 2, for $P_{\text{rot}} = 10$ d.

in the file `Bsurf_10d.gif`. Figure 4b shows that a cycle signal is no longer clearly observable when we consider the evolving surface magnetic flux. The reasons are 1) a larger degree of overlap between consecutive cycles owing to a stronger α -effect, and 2) strong polar magnetic fields in antiphase with the emerging flux.

When we decrease the rotation period to 2 d, the poleward deflection of flux tubes causes a significant difference between the dynamo waves and the surface emergence pattern, as shown in Fig. 5. An animation of surface transport is given in the supplementary file `Bsurf_2d.gif`. The tilt angles of emerging bipolar regions are much larger (around 35°) than in the solar case, leading to two latitudinal belts of opposite magnetic polarity. Meridional transport of the high-latitude belt leads to strong polar fields, with field strengths up to 30 G.

4 Conclusions and outlook

We have developed a consistently coupled model of magnetic field generation and transport in the Sun and other

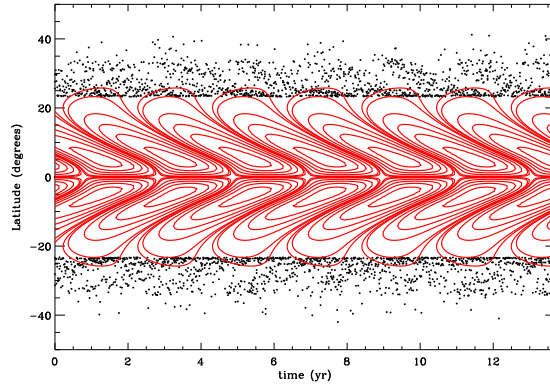


Fig. 5 Same as Fig. 3, for $P_{\text{rot}} = 2$ d. The dots are shown with one-month intervals. The emergence pattern is completely different in comparison with the dynamo wave.

cool stars. Similar to Schrijver & Title (2001) and Işık, Schüssler & Solanki (2007), we find significant polar magnetic regions for rotation periods of 10 d and 2 d, in addition to low-latitude activity. For $P_{\text{rot}} = 10$ d, the surface flux transport blurs the periodic signal from the dynamo model. This indicates that for some stars the cyclic dynamo may be hidden in a non-cyclic surface activity, which is led by the combined effects of the dynamo (cycle overlap), large tilt angles, and the meridional transport. Furthermore, for $P_{\text{rot}} = 2$ d we have found that the dynamo wave pattern and the emerging surface flux are completely different, owing to the strong poleward deflection of rising flux tubes by the Coriolis force.

As next steps, we plan to quantify the loss of magnetic flux from the dynamo layer in a consistent manner and consider it in the dynamo equations as a nonlinear term. Furthermore, we intend to develop a scheme which includes the evolving surface flux into a two dimensional flux transport dynamo as the source of the poloidal component at the bottom of the convection zone.

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